What Have We Learned About Solar Neutrinos?

by JOHN N. BAHCALL

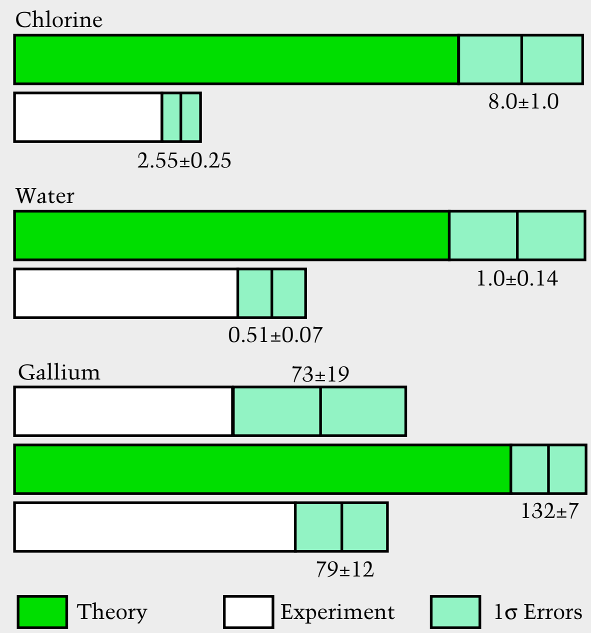
The apparent deficit of solar neutrinos may be caused by physical processes beyond the Standard Model.

THIRTY YEARS AGO Ray Davis—then working at Brookhaven and now at Pennsylvania—suggested it was practical to build an experiment to detect solar neutrinos if the event rate I calculated was correct. The proposal was based upon his experience at the Savannah River reactor trying to detect antineutrinos using a tank filled with 3,000 gallons of perchloroethylene ($C_2 Cl_4$, a common cleaning fluid), and on calculations that I had done of the event rate to be expected in a 100,000 gallon tank.

These calculations were in turn based upon nuclear physics estimates of the neutrino capture rates and solar model calculations of the neutrino fluxes. Ray was confident that he could build and successfully operate the 100,000 gallon tank, extracting the few radioactive atoms of argon produced each month due to neutrino capture by chlorine atoms ($^{37}Cl \rightarrow {}^{37}Ar$) in this huge detector. Thirty years later it is clear that he was right and the then-abundant skeptics were wrong.

At the time this chlorine experiment was proposed, the only motivation either of us presented for performing a solar neutrino experiment was to use neutrinos "to see into the interior of a star and thus directly verify the hypothesis of nuclear energy generation in stars." The hypothesis being tested was that stars like the Sun shine by fusing protons to form alpha particles, positrons, neutrinos, and thermal energy.

The original goal of demonstrating that proton fusion is the origin of sunshine has been achieved. Solar neutrinos have now been observed in four different experiments with (to usual astronomical accuracy) fluxes and energies that are in rough agreement with the expected values. The observed rates in all of the solar neutrino experiments are only about a factor of 2 or 3 less than expected (see chart on this page). Moreover, the fact that the neutrinos indeed come directly from the Sun was established by one of these experiments (Kamiokande), which showed that electrons scattered by interacting neutrinos recoil in the forward direction—away from the Sun. The characteristics of the operating solar



Comparisons between the predicted fluxes of the standard solar model and the four operating solar neutrino experiments. The unit used for the three radiochemical experiments is a solar neutrino unit, or SNU, which equals one event per second per 10^{36} target atoms. Following the experimenters, the Kamiokande result is expressed in terms of a ratio to the expected event rate. Predictions shown in this figure and quoted elsewhere in this article are from the Bahcall-Pinsonneault 1992 standard solar model with helium diffusion. The observed rates are less than the expected rates for all four experiments.

neutrino experiments were discussed by Ken Lande in the Fall 1992 *Beam Line*; they are summarized in the table on the next page. The results of these experiments represent a triumph for the combined physics, chemistry, and astronomy communities because they bring to a successful conclusion the development (which spanned much of the twentieth century) of a theory of how ordinary stars—those like the Sun—shine.

MOST OF THE CURRENT interest in solar neutrinos is focused on an application of this research that was not even discussed when the Homestake chlorine detector was proposed. Scientists have realized that they can use solar neutrinos for studying aspects of the weak interactions that are not accessible in laboratory experiments. Such searches for new physics are based upon quantitative discrepancies between the predictions for and the observations of solar neutrinos. As the experiments and the theoretical predictions have steadily improved over the past three decades, these discrepancies have resolutely refused to go away, convincing many of us who work in this field that we have been witnessing the discovery of new physics in an unexpected context.

Although thirty years ago I was a skeptic about the theory of stellar evolution and did not believe in any explanation of astronomical phenomena that required changing conventional physics, my preconceptions have since been shaken by the robustness of the theory and by the combined results of the four solar

Operating Solar Neutrino Experiments

Name	Target	Mass (tons)	Threshold (MeV)	Detector Type	Location
Homestake	^{37}Cl	615	0.86	radiochemical	Black Hills, South Dakota
Kamiokande	H_2O	680	7.5	electronic	Japanese Alps
GALLEX	^{71}Ga	30	0.2	radiochemical	Gran Sasso, Italy
SAGE	^{71}Ga	57	0.2	radiochemical	Caucasus Mtns., Russia

neutrino experiments. I now think it is most likely that we are witnessing evidence for new physics in these experiments.

Solar neutrino observations are often compared to a combined theoretical model, the standard solar model plus the Standard Model of electroweak interactions. A solar model is required to predict how many—and with what energies—neutrinos are produced in the Sun's interior. The observed luminosity of the sun (due to the same nuclear processes that produce solar neutrinos) and the other observational constraints on the solar model (including the Sun's known age, mass, chemical composition, and its many precisely measured seismological frequencies) limit the calculated fluxes to fairly narrow regions, at least by astrophysical standards (see box on next page).

The standard electroweak model—or some modification of the Standard Model—is required to determine what happens to neutrinos as they pass through the Sun and interplanetary space on their way from the solar interior to earthbound detectors. The observed discrepancies might occur if neutrinos decay in transit, or if they change from one species to another before reaching the detectors. The three radiochemical detectors register only electron neutrinos, while the only electronic detector (Kamiokande) registers both electron neutrinos and (with much reduced sensitivity) muon or tau neutrinos.

Do electron neutrinos change their flavor, or "oscillate," into hard-to-detect muon or tau neutrinos during their journey from the interior of the Sun to the Earth? The simplest version of the standard electroweak model answers "No." Neutrinos have zero masses in the Standard Model, and lepton flavor does not change. However, solar neutrinos can reveal physical processes not yet discovered in the laboratory because, for certain processes, these experiments are 10^{11} times more sensitive than terrestrial neutrino experiments. Their increased sensitivity is due largely to the fact that the elapsed time in the rest frame of a (finite-mass) neutrino is proportional to the ratio of the target–detector separation to the neutrino energy; this ratio is much larger for neutrinos originating in the Sun. Moreover, solar neutrinos traverse a far greater amount of matter than their laboratory counterparts.

THE FIRST, and for two decades the only, solar neutrino experiment uses a chlorine detector to observe electron-type neutrinos via the reaction $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$. The ^{37}Ar atoms produced by this neutrino capture process are extracted chemically from the 615 tons of perchloroethylene in which they were created; they are then counted using their characteristic radioactivity in small, gaseous proportional counters. The threshold energy is 0.8 MeV, which means (see figure on the next page) that this experiment is sensitive to the rare high-energy ^{8}B neutrinos, as well as to the lower energy *pep* and ^{7}Be neutrinos formed by electron capture on two fusing protons and on ^{7}Be nuclei. Like all solar neutrino experiments, the chlorine experiment is performed deep underground (in the Homestake gold mine, in Lead, South Dakota) in order to avoid cosmic-ray induced events that might be confused with true neutrino events.

In the Kamiokande experiment, which is carried out in Kamioka mine in the Japanese Alps, neutrino-electron scattering, $\nu + e \to \nu' + e'$, occurs inside the fiducial mass of 680 tons of ultrapure water. The scattered electrons are detected by the Cerenkov light that they produce while speeding through the water. The fact that the neutrinos are coming directly from the Sun was established by this experiment, which showed that the electrons were scattered in the forward direction, relative to the Sun. Only the rare, high-energy ^{8}B solar neutrinos can be detected in the Kamiokande experiment, for which the detection threshold is at least 7.5 MeV. The probability of detecting muon or tau neutrinos by their scattering of atomic electrons is only about 17 percent of the equivalent probability of detecting electron neutrinos at the energies for which Kamiokande is sensitive.

Two gallium experiments are in progress, GALLEX (located in the Gran Sasso underground laboratory about an hour's drive from Rome) and SAGE (in an underground chamber excavated beneath the Andyrchi mountains in the North Caucasus region of Russia). Performed by two international collaborations, these experiments provided the first observational information about the low-energy neutrinos from the basic proton-proton fusion reaction. Both experiments use neutrino absorption by gallium atoms to produce germanium, $\nu_e + {}^{71}\mathrm{Ga} \to e^- + {}^{71}\mathrm{Ge}$, which has a threshold of only 0.2 MeV for neutrino detection. Such a low threshold allows the detection of the low-energy *pp* neutrinos, for which the flux is known to an accuracy of

SOLAR NEUTRINO FLUXES

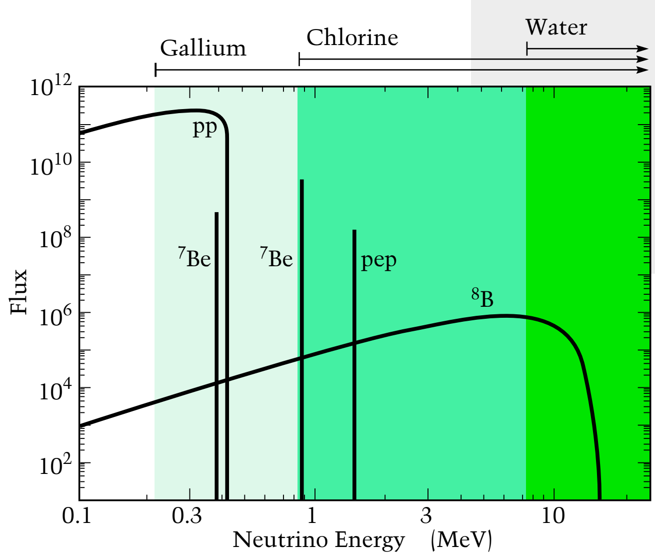
The spectrum of solar neutrinos that is predicted by the standard solar model is shown in the graph below. The basic low-energy neutrino fluxes, from *pp* and *pep* neutrinos, are most closely related to the total solar luminosity and are calculated to an estimated accuracy of about 1 percent. These reactions initiate the nuclear fusion chain in the Sun and produce neutrinos with a maximum energy of 0.4 MeV (*pp* neutrinos) or an energy of 1.4 MeV (*pep* neutrinos). Electron-capture by ^{7}Be ions produces the next most abundant source of neutrinos, a 0.86 MeV neutrino line, whose flux has an estimated theoretical error of 6 percent. Neutrinos from the beta decay of ^{8}B can have energies as high as 14 MeV; they are rare and their flux is calculated to an estimated accuracy of only 15 percent.

pp: $p + p \to {}^2\mathrm{H} + e^+ + \nu_e$

pep: $p + e^- + p \to {}^2\mathrm{H} + \nu_e$

^{7}Be: ${}^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \nu_e$

^{8}B: ${}^8\mathrm{B} \to {}^8\mathrm{Be} + e^+ + \nu_e$



The energy spectrum of neutrinos from the pp chain of interactions in the Sun, as predicted by the standard solar model. Neutrino fluxes from continuum sources (such as pp and ^{8}B) are given in the units of counts per cm^2 per second per MeV. The line fluxes (pep and ^{7}Be) are given in neutrinos per cm^2 per second. The pp chain is responsible for more than 98 percent of the energy generation in the standard solar model. Neutrinos produced in the carbon-nitrogen-oxygen CNO chain are not important energetically and are difficult to detect experimentally. The arrows at the top of the figure indicate the energy thresholds for the ongoing neutrino experiments.

LANL (Thomas J. Bowles)

Containers of gallium in the SAGE experiment, which detects solar neutrinos down to a threshold energy of 0.2 MeV

1 percent. The GALLEX and the SAGE experiments use radiochemical procedures to extract and count a small number of atoms from a large detector, similar to what is done in the Homestake chlorine experiment.

All four solar neutrino experiments yield fluxes significantly less than predicted and well outside the combined errors (see chart on page 11). One fact is immediately apparent: the disagreement between theory and experiment seems to depend upon the threshold for neutrino detection, being a factor of about 3.1 for the Homestake chlorine experiment (0.8 MeV threshold) and only 2.0 for the Kamiokande water experiment (7.5 MeV threshold). These two experiments are primarily sensitive to the same neutrino source, the rare, high-energy ^{8}B solar neutrinos; their sensitivity to threshold energy suggests that some physical process, in addition to the familiar nuclear beta-decay, changes the energy spectrum of these neutrinos before they reach the detectors.

THE MARKED discrepancies between predicted and measured neutrino fluxes is known as the "solar neutrino problem." It cannot be "solved" by making plausible changes in the standard solar model or by postulating that only one or two solar neutrino experiments are incorrect. As I argue in the boxes on pages 15 and 16, the least radical solutions are: at least three of the four experiments are wrong, or something unexpected happens to neutrinos after they are created in the solar interior. The latter solution requires a slight but important generalization of the simplest version of the standard electroweak theory.

I use only the published results of the four ongoing solar neutrino experiments and the most robustly predicted neutrino fluxes from published standard solar models. As a measure of the uncertainty in the predictions, I use the total range of the calculated neutrino fluxes from the 11 recently-published solar model calculations carried out by different research groups using independent stellar evolution codes and employing a wide range of possible input parameters and approximations to the stellar physics.

Some particle physicists have expressed skepticism about the solar neutrino problem because the calculated flux of high-energy neutrinos from ^{8}B beta-decay depends strongly upon the central temperature of the Sun. A related concern is being discussed among nuclear physicists, who are using recent experiments and new calculations to determine whether the 9 percent uncertainty estimated by CalTech physicists for the production cross section of ^{8}B nuclei in the Sun is indeed valid. The calculated flux of ^{8}B neutrinos is proportional to this cross section.

I personally believe that the previously estimated nuclear physics uncertainties are reasonable. But for the purposes of the present argument—and to allay skepticism—I

The Chlorine-Water Problem

THE HOMESTAKE AND THE KAMIOKANDE solar neutrino experiments are not consistent with each other unless some physical process—not included in standard electroweak theory—affects the energy spectrum of ^{8}B neutrinos. The argument leading to this conclusion goes as follows:

The most recent result of the Kamiokande experiment for the rare ^{8}B neutrinos is

$$\text{Flux}(^8\text{B}) = (2.89 \pm 0.41) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}, \quad (1)$$

where I have combined quadratically (both here and below) the statistical and systematic errors. I have shown elsewhere that if standard electroweak theory is correct, then the shape of the energy spectrum from ^{8}B solar neutrinos must be the same (to 1 part in 10^5) as the shape determined by laboratory experiments. The absorption cross section is known accurately for ^{8}B neutrinos with a standard energy spectrum incident on a ^{37}Cl nucleus. Therefore, if standard electroweak theory is correct, the capture rate in the Homestake chlorine experiment from the ^{8}B neutrino flux observed in the Kamiokande experiment should be

$$\text{Rate in Cl}\ (^8\text{B}) = (3.21 \pm 0.46)\ \text{SNU}, \quad (2)$$

where 1 SNU = 1 neutrino capture per 10^{36} target atoms per second. But the observed rate in the chlorine experiment from *all* neutrino sources is

$$\text{Obs Rate in Cl} = (2.55 \pm 0.25)\ \text{SNU}. \quad (3)$$

Subtracting the rate due to ^{8}B neutrinos as determined by the Kamiokande experiment (2) from the rate due to all neutrino sources (3), we find that the best estimate for the capture rate in the chlorine experiment from all sources *except* ^{8}B neutrinos, assuming standard electroweak theory to be correct, is

$$\text{Obs Rate in Cl}(pep + {}^7\text{Be} + \text{CNO}) = -0.66 \pm 0.52\ \text{SNU}, \quad (4)$$

where CNO represents the sum of all neutrino-producing reactions in the CNO cycle. This negative value for the sum of the capture rates from three different neutrino sources is the simplest expression of the "solar neutrino problem." It is independent of the solar model used.

Although the best estimate for the residual capture rate for *pep,* ^{7}Be and CNO solar neutrinos is negative, the physical capture rate for any set of neutrino fluxes has to be positive definite. Adopting the conservative procedure used by the Particle Data Group in analogous discussions (for example, upper limits to neutrino masses), we find:

$$\text{Rate in Cl}(pep + {}^7\text{Be} + \text{CNO}) \leq 0.68\ \text{SNU (95\% conf.)}. \quad (5)$$

We can refine this result by utilizing the fact that the flux of neutrinos from the *pep* reaction is directly related to the basic *pp* reaction, which is the initiating fusion reaction that produces nearly all of the solar luminosity in standard solar models. The total spread in the calculated capture rates for *pep* neutrinos for the 11 recently published standard solar models (calculated with different codes and input parameters) is 0.22 ± 0.01 SNU. Subtracting this accurately-known *pep* flux from the the upper limit for the three neutrino sources shown in (5), we obtain:

$$\text{Rate in Cl}(^7\text{Be} + \text{CNO}) \leq 0.46\ \text{SNU (95\% conf.)}. \quad (6)$$

The ^{7}Be neutrino flux is predicted with reasonable accuracy; the results from the 11 different standard solar models yield the value

$$\text{SSM Rate in Cl}(^7\text{Be}) = 1.1 \pm 0.1\ \text{SNU}. \quad (7)$$

Thus the upper limit on the sum of the capture rates from ^{7}Be and CNO neutrinos is significantly less than the lowest value predicted for ^{7}Be neutrinos alone, by any of the 11 recent standard solar models. I did not subtract the CNO neutrino capture rate from the sum of the two rates because the conflict between the measurements and the standard models (solar and electroweak) is apparent without this additional step and because the estimated rate from CNO neutrinos, 0.4 ± 0.08 SNU, is more uncertain than for the other neutrino fluxes being considered.

The Gallium Problem

THE GALLEX AND THE SAGE gallium solar neutrino experiments have reported consistent neutrino capture rates (respectively, 79±12 SNU and 73±19 SNU). From the weighted average of their results, the best estimate for the gallium rate is

$$\text{Obs Rate in Ga} = 77 \pm 10 \text{ SNU}. \quad (8)$$

All standard solar models yield essentially the same predicted event rate from *pp* and *pep* neutrinos, 74 ± 1 snu. Subtracting this rate from the total observed rate, one finds that the residual rate from ^{7}Be and ^{8}B solar neutrinos in gallium is small,

$$\text{Rate in Ga}(^7\text{Be} + {}^8\text{B}) = 3 \pm 10 \text{ SNU}, \quad (9)$$

which implies that the upper limit on this rate is

$$\text{Rate in Ga}(^7\text{Be} + {}^8\text{B}) \leq 22 \text{ SNU (95\% conf.)}. \quad (10)$$

This combined ^{7}Be and ^{8}B rate is less than the predictions from ^{7}Be neutrinos alone for all 11 recently-published standard solar models.

Moreover, one should take account of the ^{8}B neutrino flux that is observed in the Kamiokande experiment, which in the gallium experiments translates to

$$\text{Rate in Ga}(^8\text{B}) = 7.0^{+7}_{-3.5} \text{ SNU}, \quad (11)$$

where the quoted errors are dominated by uncertainties in the calculated neutrino absorption cross sections and I have assumed that the shape of the energy spectrum of ^{8}B solar neutrinos is the *same* as measured in the laboratory. Subtracting this rate for ^{8}B neutrinos from the combined rate of ^{7}Be and ^{8}B neutrinos, one again finds that the best-estimate flux for ^{7}Be neutrinos is negative.

$$\text{Rate in Ga}(^7\text{Be}) = -4^{+11}_{-12} \text{ SNU}. \quad (12)$$

Following the same statistical procedure as described earlier, one can set a conservative upper limit on the ^{7}Be neutrino flux using the gallium and the Kamiokande measurements:

$$\text{Rate in Ga}(^7\text{Be}) \leq 19 \text{ SNU (95\% conf.)}. \quad (13)$$

The predicted rate given by the 11 standard solar models is

$$\text{SSM Rate in Ga}(^7\text{Be}) = 34 \pm 4 \text{ SNU}. \quad (14)$$

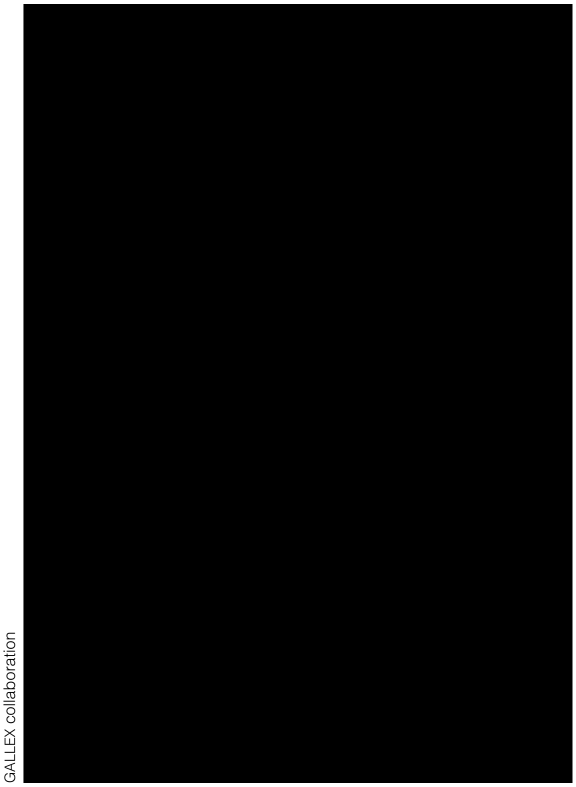
The discrepancy between these two equations is a quantitative expression of the gallium solar neutrino problem.

The present results for the gallium experiments are close to being in conflict with a model-independent, unrealistically conservative upper limit on the counting rate. This minimum counting rate of 80 SNU is calculated assuming only that the Standard Model is correct and that the Sun is currently producing nuclear fusion energy at the same rate at which it is losing photon energy from the surface. To reach the lower limit of 80 SNU in a solar model, one must set equal to zero the rates of all nuclear reactions that produce ^{7}Be in the sun. We know that this limit cannot be satisfied in practice because we observe high energy ^{8}B neutrinos and ^{8}B is produced by proton capture on ^{7}Be—and because the cross section for creating ^{7}Be has been measured in the laboratory to be competitive with the other solar fusion rates.

will assume that *all* of the published laboratory measurements and theoretical nuclear physics calculations are wrong and that the cross section for ^{8}B production in the Sun has somehow been adjusted to yield the flux measured for these high-energy neutrinos in the Kamiokande experiment. This implies that the laboratory nuclear physics measurements are in error by a factor of 2, not by 9 percent. Since I adopt the ^{8}B neutrino flux measured in the Kamiokande experiment, the ^{8}B flux used in the following discussion is independent of any solar-model uncertainties (including the sensitive temperature dependence). This procedure removes a principal reason for skepticism. Even this extreme assumption does not avoid the necessity for new physics, as we shall see.

The argument described here, most of which was developed in a slightly different form by Hans Bethe and myself in 1990, avoids all uncertainties associated with the solar model calculation of the ^{8}B flux. We pointed out that taking the measured rate for ^{8}B neutrinos from the Kamiokande experiment implies an ^{8}B event rate in the Homestake experiment that is slightly in excess of the total measured rate from *all* neutrino sources. In other words, a partial rate exceeds the total rate, which makes no sense unless something happens to the lower-energy part of the ^{8}B electron neutrino flux—that part of the flux which is visible in the Homestake chlorine experiment but not in the Kamiokande water experiment. This direct comparison of two experiments—independent of any solar model considerations—suggests

One of the large containers of gallium used in the GALLEX solar neutrino experiment, which is located in the Gran Sasso underground laboratory in Italy.



GALLEX collaboration

that a new physical process causes the discrepancy between the experiments.

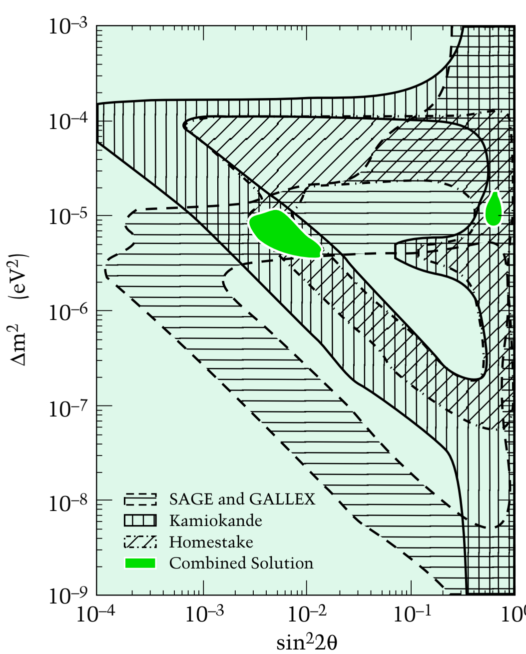
There are actually *two* solar neutrino problems: the chlorine-water problem and the gallium problem. In the box on page 15, I show why the measured rates of the chlorine and the water experiments are inconsistent with each other, unless some new physical process—not included in the standard electroweak model—changes the shape of the energy spectrum of ^8B neutrinos in transit to the detector. In the box on page 16 I argue that the gallium experiments are inconsistent with robust predictions of the standard solar model.

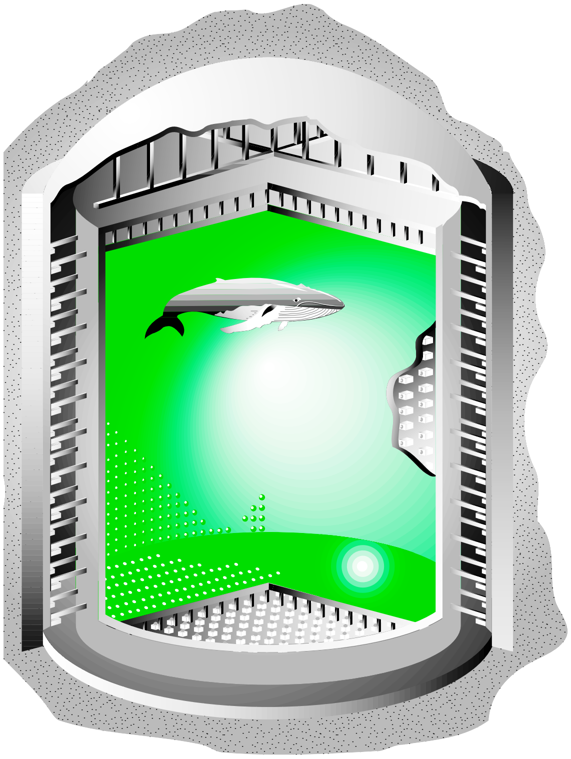
Let me assume for purpose of discussion that a correct solar neutrino experiment must yield a rate for the ^7Be neutrino flux that is consistent (at the 95% confidence level) with nothing happening to solar neutrinos after they are created (i.e., the standard electroweak theory) and with the value of the ^7Be neutrino flux that is predicted by the standard solar model. If these assumptions are both correct, then at least three of the four operating solar neutrino experiments must be wrong. Either the Homestake or the Kamiokande experiment must be wrong in order to avoid the chlorine-water problem (see box on page 15) and both the GALLEX and SAGE experiments must be wrong in order to avoid the gallium problem (see box on page 16).

THE TWO MOST POPULAR mechanisms for explaining the solar neutrino problem via new physics are vacuum neutrino oscillations, first discussed in this connection by Vladimir Gribov and Bruno Pontecorvo in an epochal paper, and matter-enhanced neutrino oscillations, the MSW effect, a beautiful idea discovered by Lincoln Wolfenstein and also by Stanislav Mikheyev and Alexei Smirnov. Other solutions have been proposed for the solar neutrino problem that involve new weak interaction physics, such as neutrino decay, rotation of the neutrino magnetic moment, and matter-enhanced magnetic moment transitions.

If new physics is required, then the MSW effect, which provides a natural extension of the simplest version of standard electroweak theory, is in my view the most likely candidate. According to this explanation, electron neutrinos are transformed into muon or tau neutrinos as a result of their interaction with electrons in the Sun. The MSW effect only occurs if neutrinos have an "identity crisis"—i. e., the neutrinos produced in nuclear beta decay are mostly electron neutrinos but have a non-vanishing probability (described by a mixing angle θ) of being either a muon or a tau neutrino. Non-zero neutrino masses are required for this effect to occur in a plausible manner, but the masses and mixing angles indicated by experiment are within the range expected on the basis of grand unified theories. If the MSW effect is the explanation of the solar neutrino problem, then the Homestake, Kamiokande and the two gallium experimental results can all be explained (see graph) if at least one neutrino coupled to the electron neutrino has a mass m and a mixing angle θ that satisfy: $m^2 \sim 10^{-5}$ eV^2 and $\sin^2 2\theta \sim 10^{-2}$ or $m^2 \sim 10^{-5}$ eV^2 and $\sin^2 2\theta \sim 0.6$.

The regions in mass and mixing angle space that are consistent with all four solar neutrino experiments. This figure, prepared by Naoya Hata and Paul Langacker, shows two possible solutions of the solar neutrino problem that make use of the MSW effect. Both solutions correspond to some neutrinos having a mass of order 0.003 eV.





Artist's conception of the Super Kamiokande detector now under construction in the Japanese Alps. This huge tank, containing 50,000 tons of ultrapure water viewed by over 11,000 phototubes, will be used to search for proton decay and to detect solar neutrinos, among other goals. (The 60 foot humpback whale is shown only for size comparison and is not a part of this experiment!)

New solar neutrino experiments now under construction will soon test the proposition that new physics is required, independent of uncertainties due to solar models. The first of these experiments (the Sudbury Neutrino Observatory, or SNO, and Super Kamiokande) are expected to become operational in 1996 and to increase the counting rates by two orders of magnitudes over those observed in the four pioneering solar neutrino experiments. (see "New Solar Neutrino Detectors," by Ken Lande, Fall 1992 *Beam Line*, page 9, for a brief discussion of these experiments). These two experiments and another called ICARUS (being developed at CERN) can determine the shape of the ^{8}B solar neutrino energy spectrum and whether or not electron neutrinos have oscillated into some other kind of neutrino. And a liquid scintillator detector named BOREXINO will provide the first direct measurement of the crucial flux of ^{7}Be neutrinos.

In the meantime, scientists and engineers can take great satisfaction that thirty years of their collective efforts have provided direct experimental confirmation, in the form of measured neutrinos, of the theory of how ordinary stars shine. Physicists and chemists have collaborated to perform extraordinarily sensitive experiments that measure accurately the event rates produced by solar neutrinos. Astrophysicists have successively refined their calculations of solar models until they are in agreement with a wealth of detailed (non-neutrino) solar observations. Their theoretical calculations of the neutrino interaction rates have been steadily improved with the help of new experimental data. Finally, theoretical physicists have invented new physical processes that extend the standard electroweak model in plausible ways and which, in addition to explaining the operating experiments, make testable predictions for the next round of solar neutrino experiments. Important limits on the magnitudes of possible non-standard neutrino interactions have already been established by the existing experiments. After the new experiments begin operating, we should finally learn whether or not we have stumbled by accident upon new particle physics while trying to test the theory of how the Sun shines.